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OIL VELOCITIES IN THE **WEEKS** ISLAND MINE  
DURING OIL RECYCLE EXERCISES

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Abstract

As part of the Strategic Petroleum Reserve (SPR), the Weeks Island oil storage site is a converted salt mine that contains approximately 73 million barrels of oil overlying 0.5 million barrels of brine. The oil is contained on two levels of the converted mine which are connected by a number of shafts and openings. Oil recycle exercises are periodically conducted to test the oil fill and withdrawal systems in which oil is simultaneously injected and withdrawn from two different locations in the lower level, and brine may be transported around the lower level of the mine by the movement of the oil.

For the maximum expected oil recycle rate of 593,000 BPD, the velocities vary from 0.16 ft/sec near the fill holes, to 0.001 **ft/sec** in the main part of the mine, to 0.025 ft/sec near the service shaft. Most of the flow is in the southern portion of the lower level. Negligible flow through the upper level of the mine is calculated. The oil velocities vary directly with the oil recycle rate, and the flow pattern is essentially unchanged down to a recycle rate of 59,300 BPD, the minimum value investigated. Based on these low velocities, brine movement due to oil recycle is considered to be unlikely in the main part of the mine and in the area of the service shaft. Brine movement in the fill holes is the subject of a separate investigation and is not addressed in this report.

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## I. Introduction

Approximately 73 million barrels of oil are stored in the converted Weeks Island mine as part of the Strategic Petroleum Reserve (SPR). In addition to the oil, approximately 0.5 million barrels of brine are in the bottom of the mine. In order to exercise the oil fill and withdrawal systems, oil recycle exercises are conducted in which oil is simultaneously injected into and withdrawn from the mine. Quantification of the oil velocities in the Weeks Island mine is desired to determine if brine is entrained or moved by the oil during these exercises. Knowledge of the movement of the brine due to various activities is important in monitoring the brine levels in the mine in order to determine potential water seepage or leakage. In addition, knowledge of the fraction of the oil influenced by these recycle exercises and the time scale for oil movement between the injection and withdrawal locations is of general interest. Therefore, a model for the oil velocities in the Weeks Island mine has been developed and applied to an oil recycle exercise.

The Weeks Island storage site is a converted salt mine that was originally owned by the Morton Salt Company. The site was purchased by the Department of Energy (DOE) in 1976 and converted to oil storage. The mine conversion process included construction of oil withdrawal and filling capability and the bulkheading of openings to upper mined areas and to the surface. A number of drain holes were also drilled between the two levels to allow the oil to drain from the upper level to the lower level. Additional communication between the two levels is provided by the Upper Level Access Drift. Further details on the history, mine characteristics, and the mine conversion activities are summarized in the Overview of Underground Construction (PB-KBB (1982)).

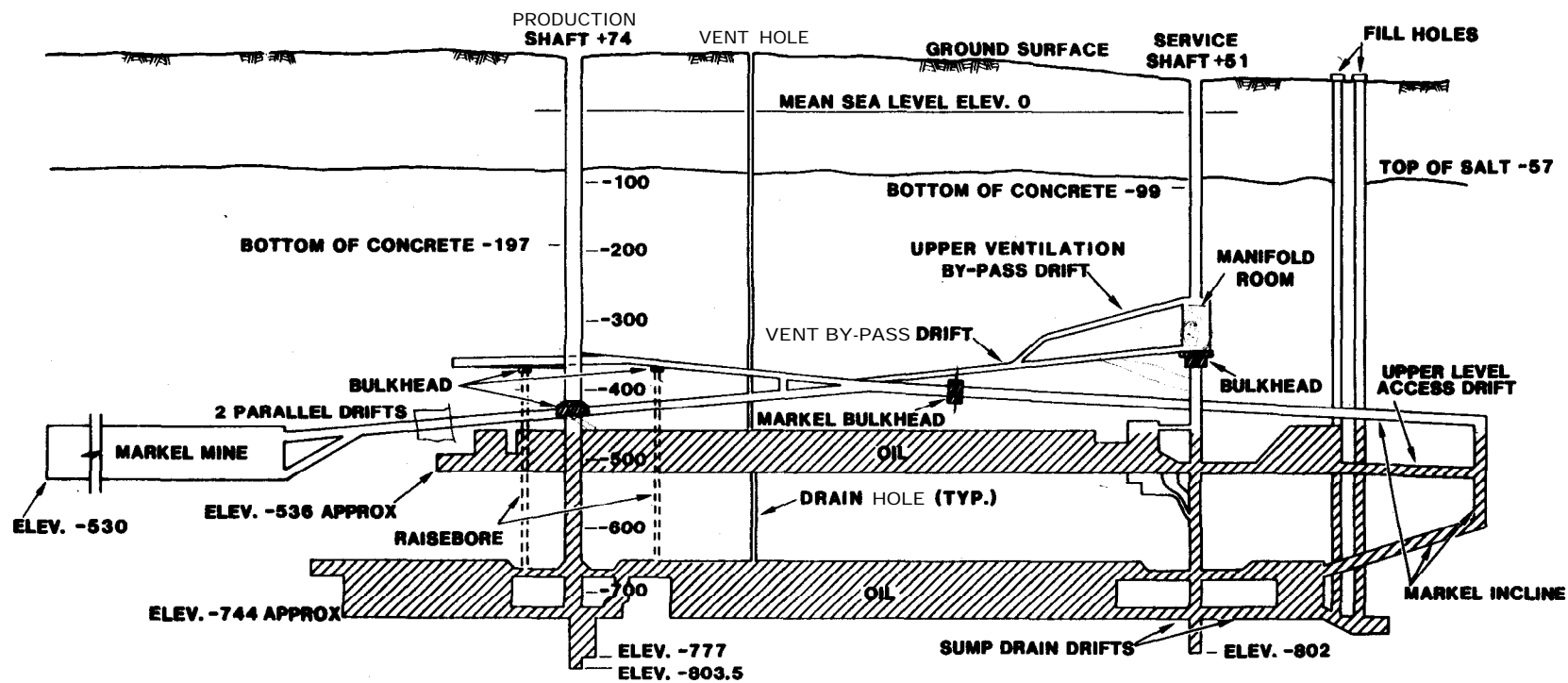
Figure 1 shows a section of the Weeks Island mine. The mine has two levels, an upper level at a nominal floor elevation of -536 feet MSL (Mean Sea Level) and a lower level at a nominal floor elevation of -744 feet MSL. There are a number of entries to the mine from the surface. They are the service shaft, the production shaft, and the fill holes. The service shaft goes from the surface through both levels of the mine. This shaft contains the oil withdrawal pumps for the mine which are located in the sump at the lower level. The pumps discharge through piping in the manifold room, which is an enlarged area of the service shaft, at -355 feet MSL. The production shaft, which was used by Morton Salt, goes from the surface to the

lower level of the mine but is presently bulkheaded off just above the upper level. The fill holes go from the surface to the lower level of the mine. During a recycle exercise, oil is simultaneously injected through the fill holes and withdrawn at the service shaft sump.

The plan view of the mine is given in Figures 2 through 4. Figure 2 shows how the two levels overlay each other. The upper level lies over the western half of the lower level and is much smaller. Approximately one third of the oil is contained in the upper level with the remaining two thirds of the oil in the lower level. Figures 3 and 4 show the details of the upper and lower level, respectively. The various rows and columns of the mine are **labelled** for identification. Rows (east-west corridors) have a letter designation while columns (north-south corridors) are identified by numbers. The letters and numbers both start in the southwest corner. Therefore, row A is on the south side of the level, while column 1 is on the west side. Details of the fill hole and service shaft areas are shown in Figures 5 and 6. Both levels are of the room and pillar type. Trenches were dug in both levels during the mine conversion work to facilitate drainage of the oil to the service shaft sump and to minimize the amount of unrecoverable oil. Rooms of various heights are noted, especially in the lower level, where they vary from nominal heights of 25 feet to 75 feet.

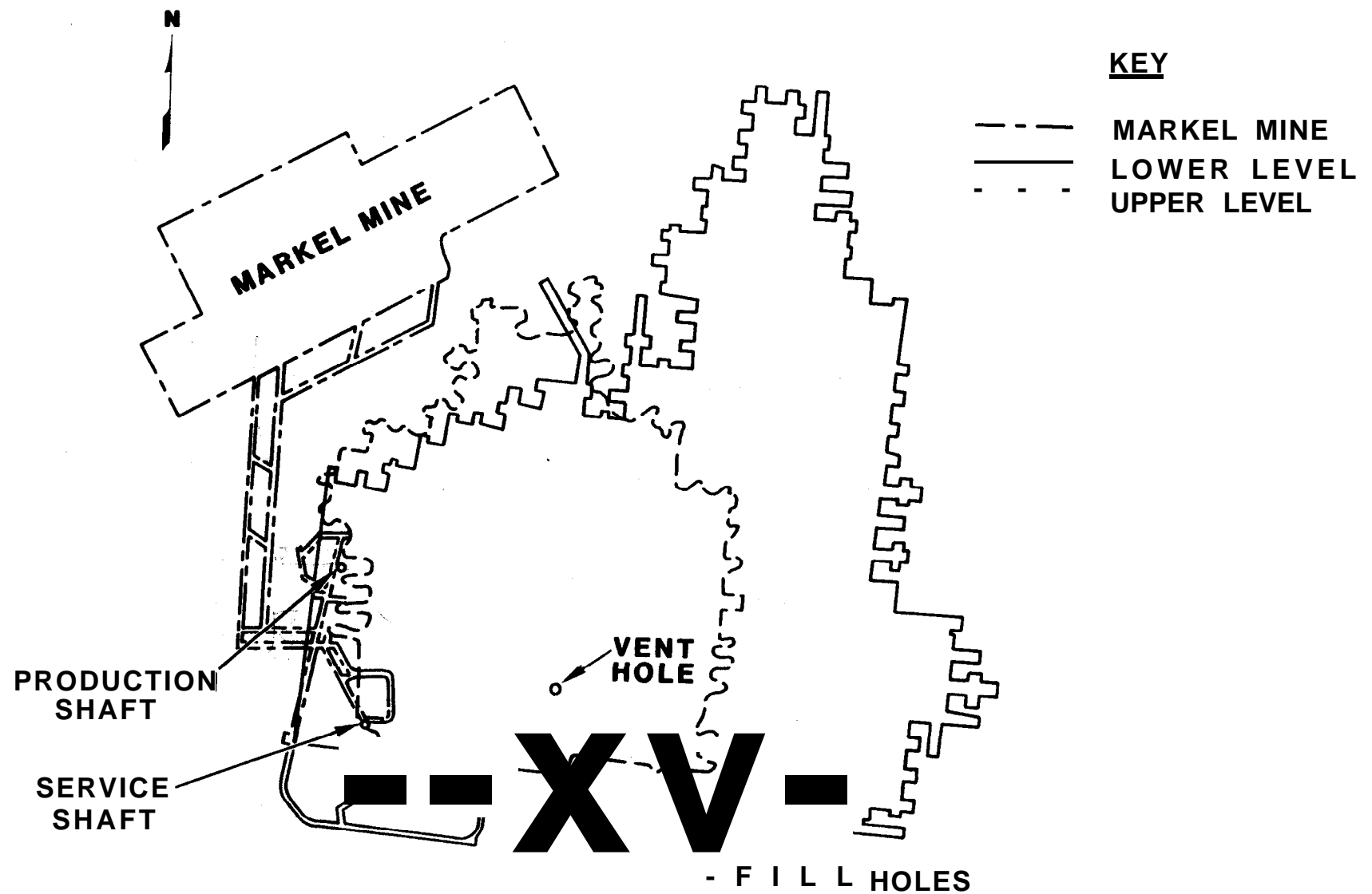
During oil recycle exercises, oil is injected into the lower level of the mine through the two fill holes which are at the southern edge of the mine just to the east of center. Oil is withdrawn through the service shaft which is in the southwest corner of the lower level. The design oil withdrawal rate of the service shaft pumps is 593,000 BPD (barrels per **day**). Since the fill and withdrawal locations for a recycle exercise are both in the lower level of the mine, the oil velocity will be greatest on this level. Circulation through the upper level of the mine is expected to be negligible, and the modeling effort is concentrated on the fluid dynamics in the lower level. The model is developed in the next section.

The oil velocities presented in this report are for the main area of the Weeks Island mine and in the drifts near the service shaft. Details of the velocities in the fill hole area including the fill hole drifts and in the service shaft and sump have not been evaluated. Fill hole velocities, including the effects of the possible brine entrainment by the incoming oil jet, are being investigated separately. A detailed evaluation of the velocities in the service shaft sump is not planned at the present time.



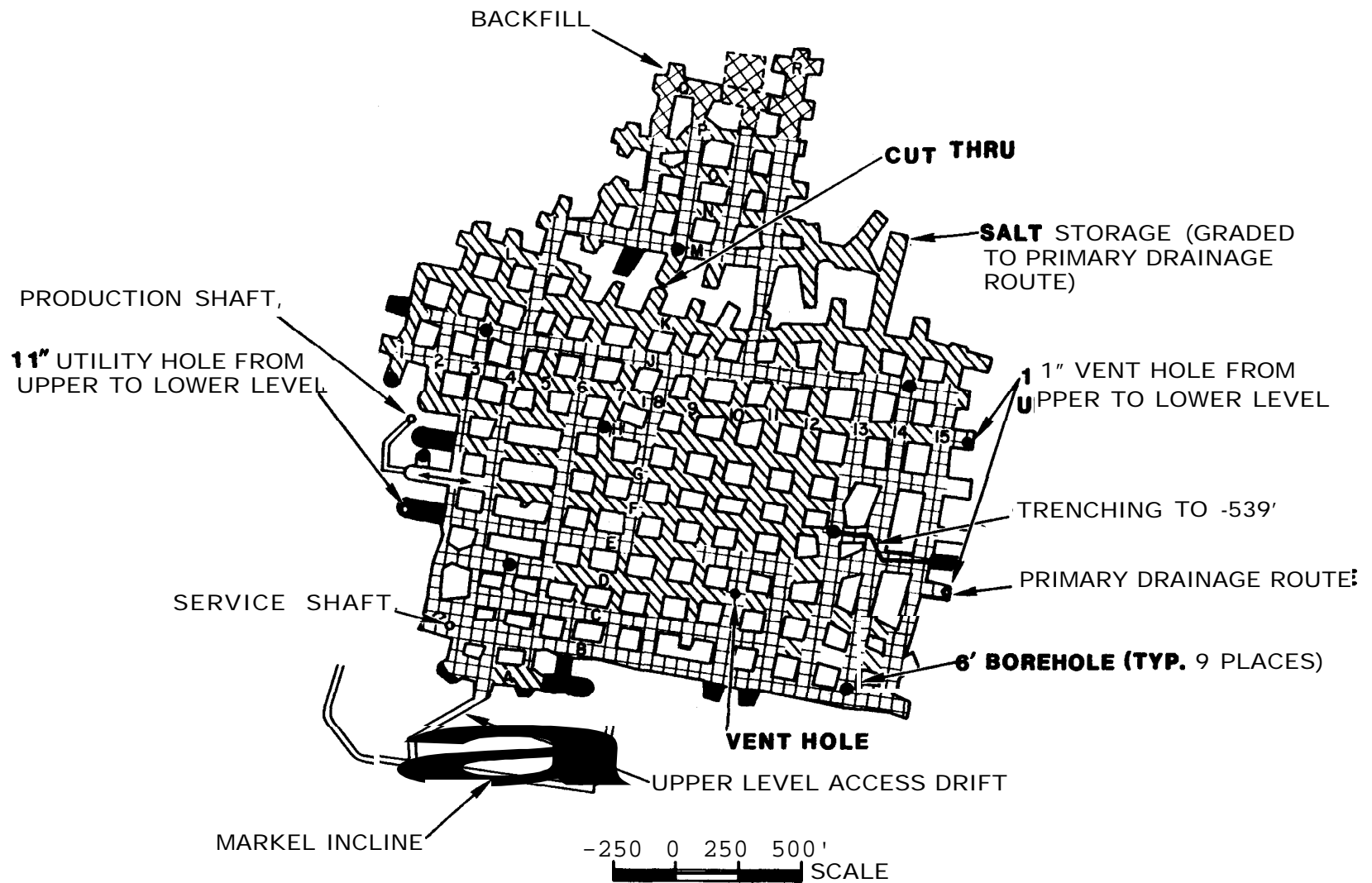
NOTE: BASED ON FIGURE 2.1 OF PB-KBB (1986).

Figure 1. Upper and lower level schematic.



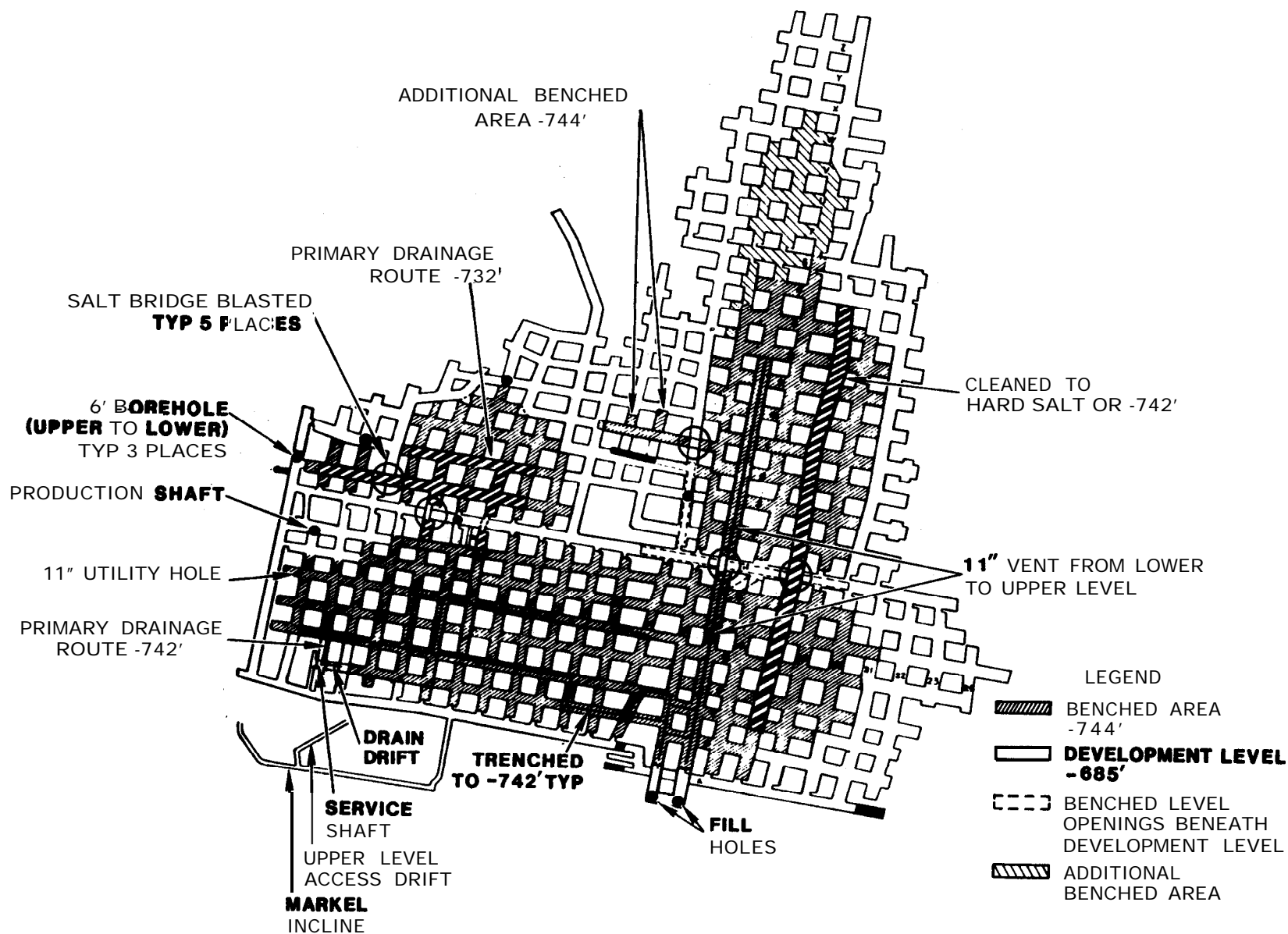
NOTE: BASED ON FIGURE 1.1 OF BEASLEY, et al. (1985)

Figure 2. Upper and lower level plan view.



NOTE: BASED ON SPR DRAWING **WI-JD-280, MI-2252.**

Figure 3. 'Upper level plan view.



**NOTE:** BASED ON SPR DRAWING WI-JD-280, MI-2253.

-250 0 250 500'  
SCALE

Figure 4 Lower level plan view.

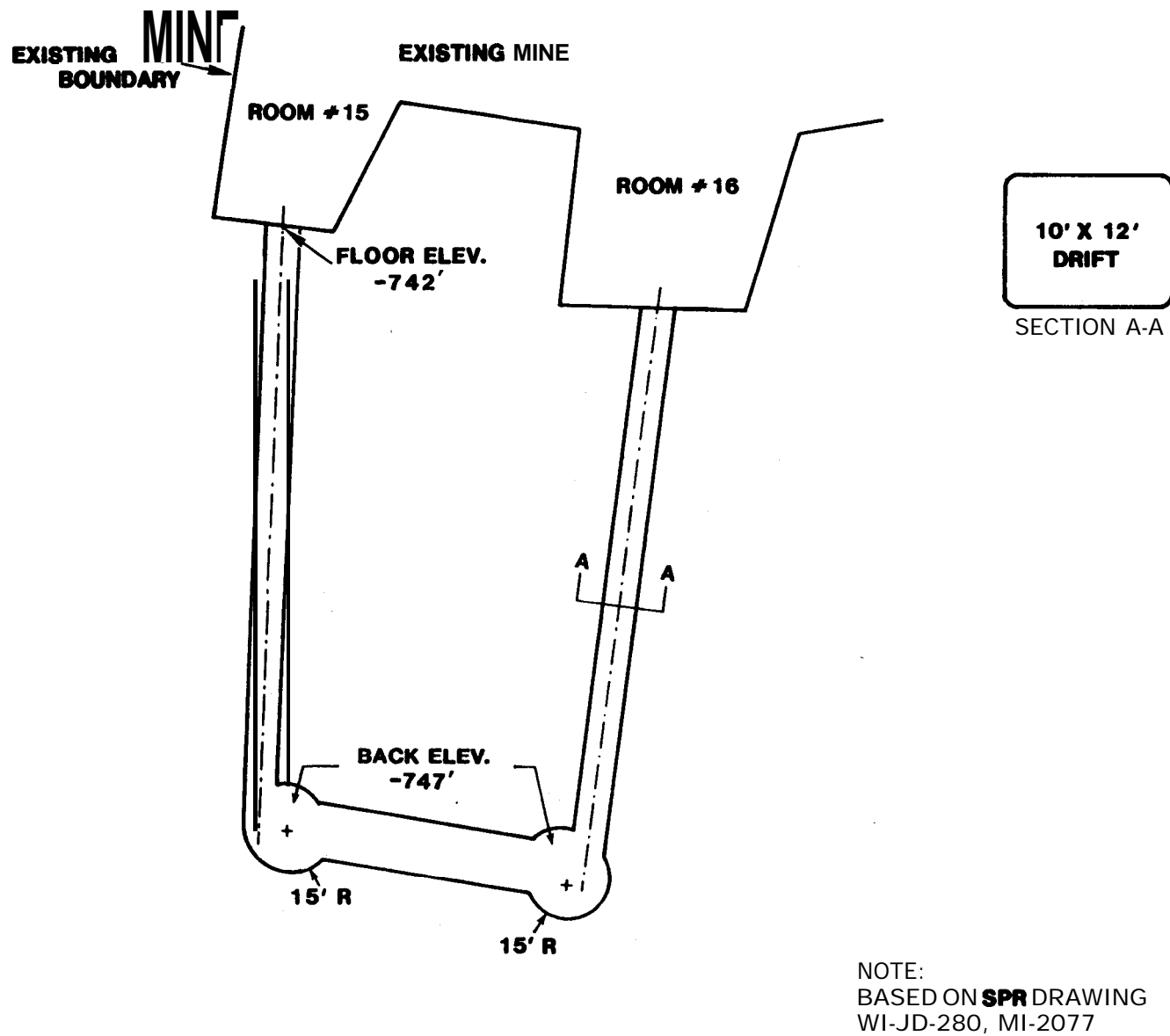


Figure 5. Fill hole details,

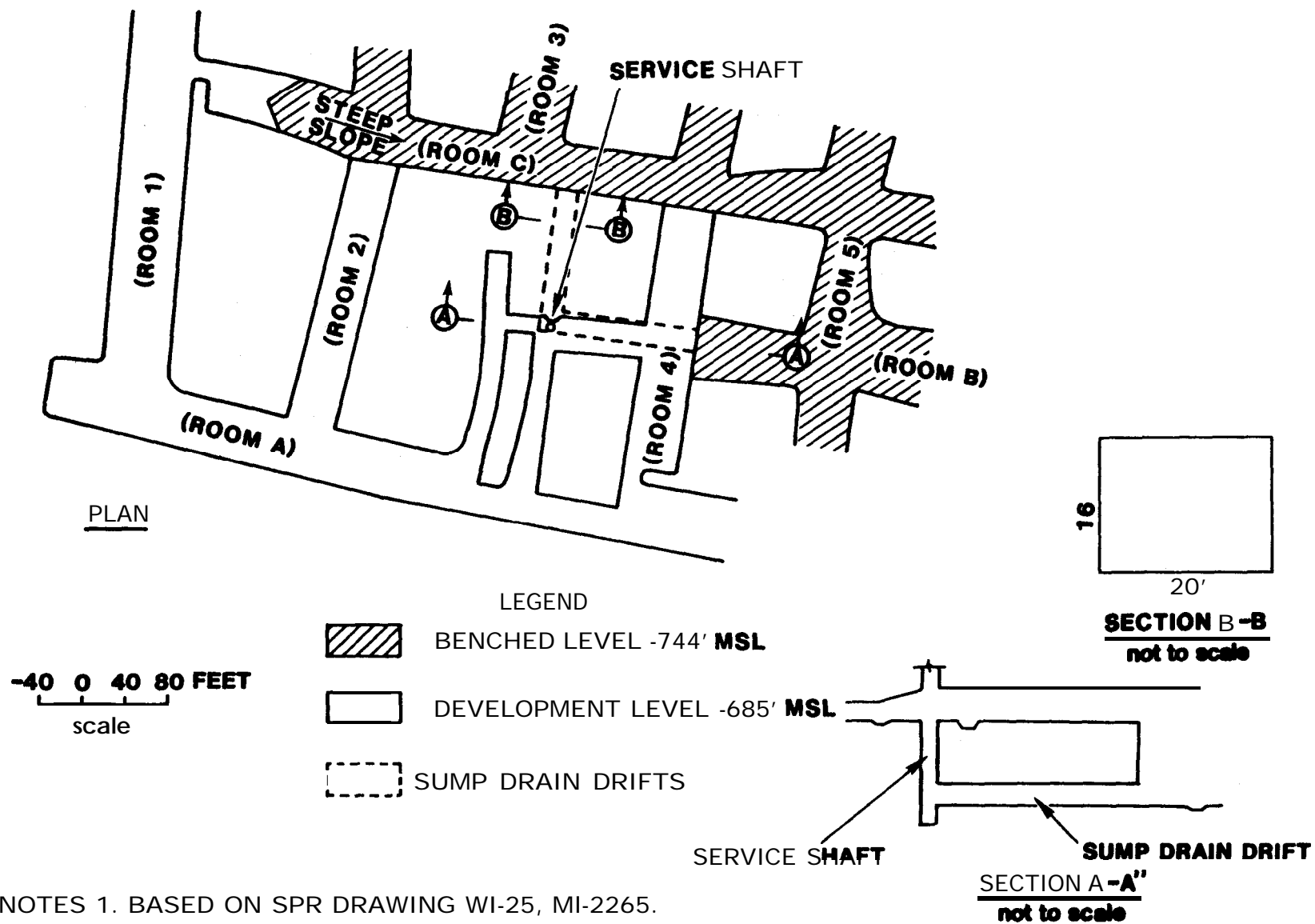


Figure 6. Service Shaft details.

## II. Model Development

The fluid flow of the oil in the Weeks Island mine will be treated as a steady state process. The oil level is constant since the oil addition rate and withdrawal rate are assumed to be equal. The room and pillar geometry suggests application of the network method similar to that used for electrical systems as schematically shown in Figure 7. The resistance to fluid flow between the corridors is modeled, and the flow in the entire mine can be solved. Conservation of mass is satisfied at each node and momentum is conserved in the flow of oil between nodes.

### Continuity

For steady state conditions, the flow into and out of each node is equal to the mass source rate as depicted in Figure 8a, or:

$$\dot{m}_w - \dot{m}_e + \dot{m}_s - \dot{m}_n = \Gamma. \quad (1)$$

or

$$\rho V_w A_w - \rho V_e A_e + \rho V_s A_s - \rho V_n A_n = I'. \quad (2)$$

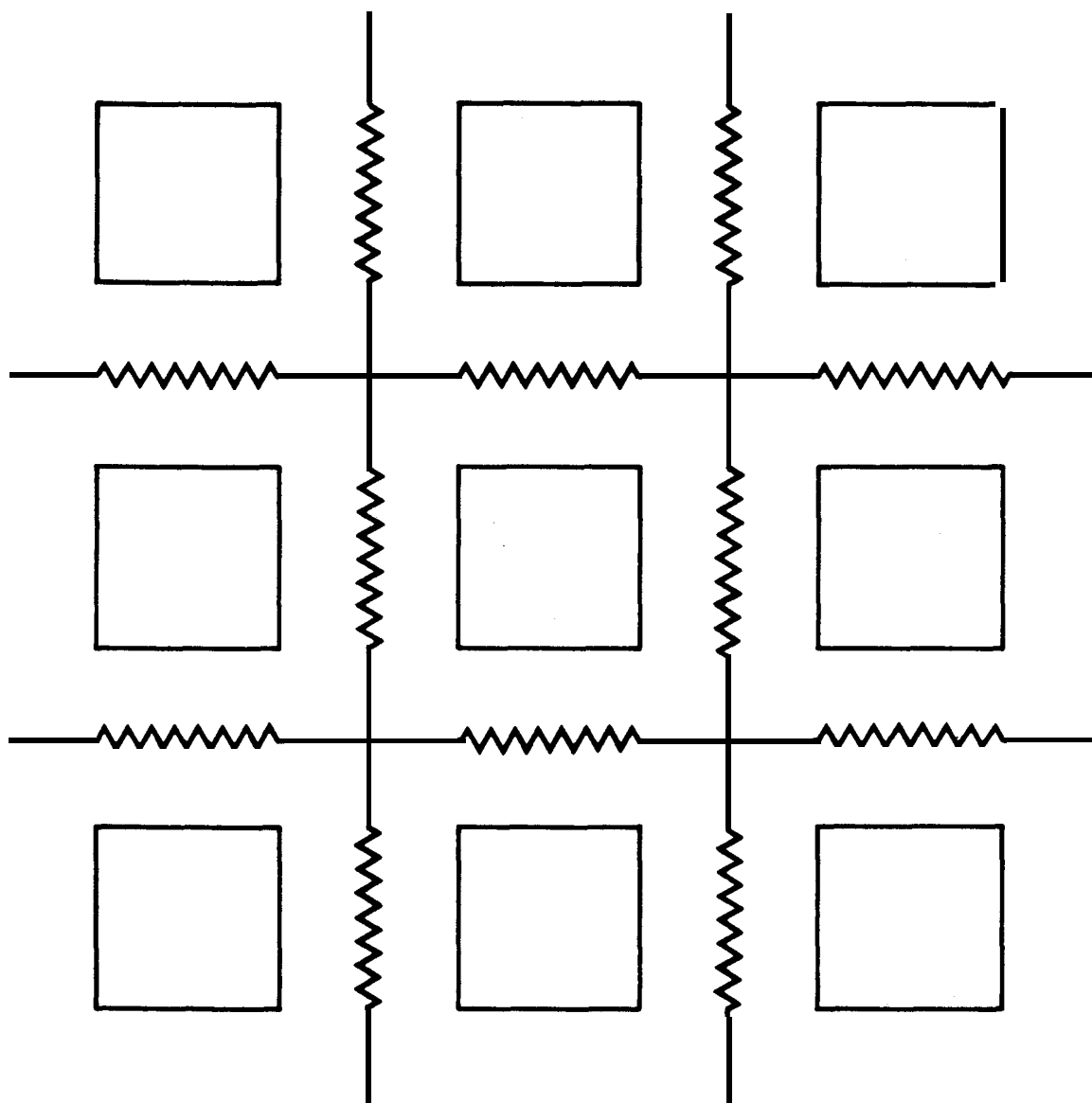
where  $\Gamma$  is the mass source for the node. For most of the nodes,  $I'$  is equal to 0. For the fill hole and the service shaft nodes, the mass source values are equal to the mass source and sink rate, respectively.

### Momentum

Assuming steady state, neglecting the momentum flux term as is usually done for liquid flows, and evaluating the pressures at a common elevation, conservation **of momentum** as shown in Figure 8b can be written as:

$$P_i - P_o = - (K_{i-o} + f \frac{L}{D}) \frac{\rho V_i |V_i|}{2 g_c} \quad (3)$$

where  $f$  is the friction factor and  $K$  is the pressure loss factor or  $K$  factor. The  $K$  factor includes losses due to turns, expansions and contractions, and other geometrical considerations. These terms are discussed in



. NODES OR PRESSURES


 FLOW RESISTANCE OR  
 PRESSURE DIFFERENCE

Figure 7. Application of network method.

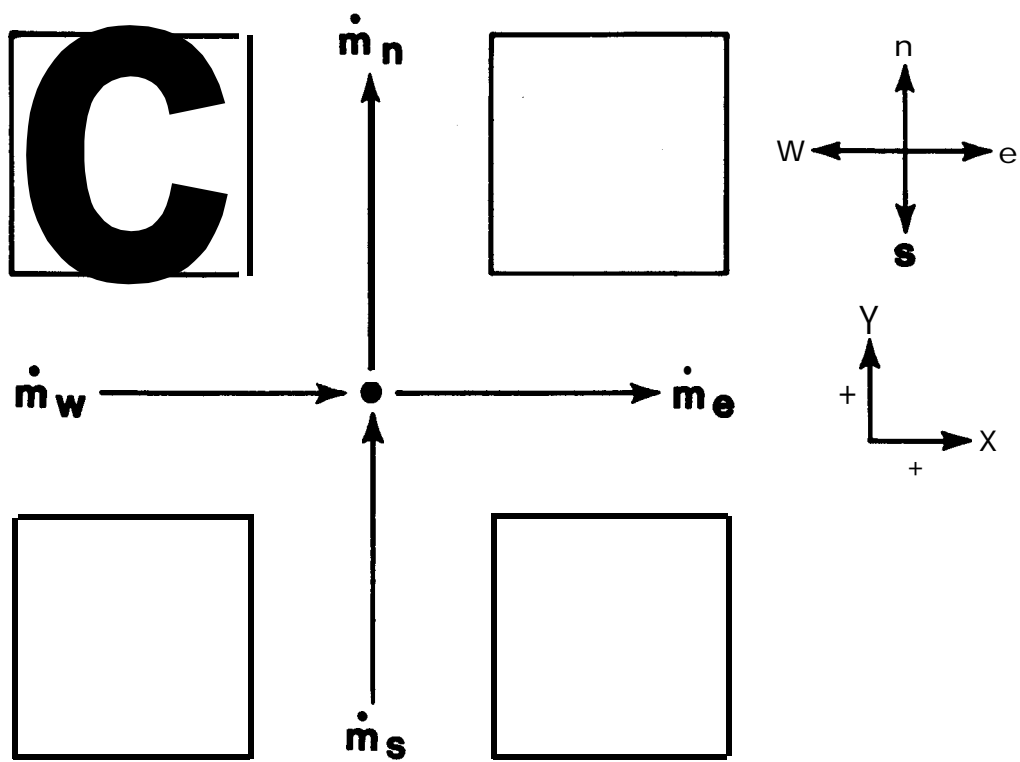


Figure 8a. Continuity.

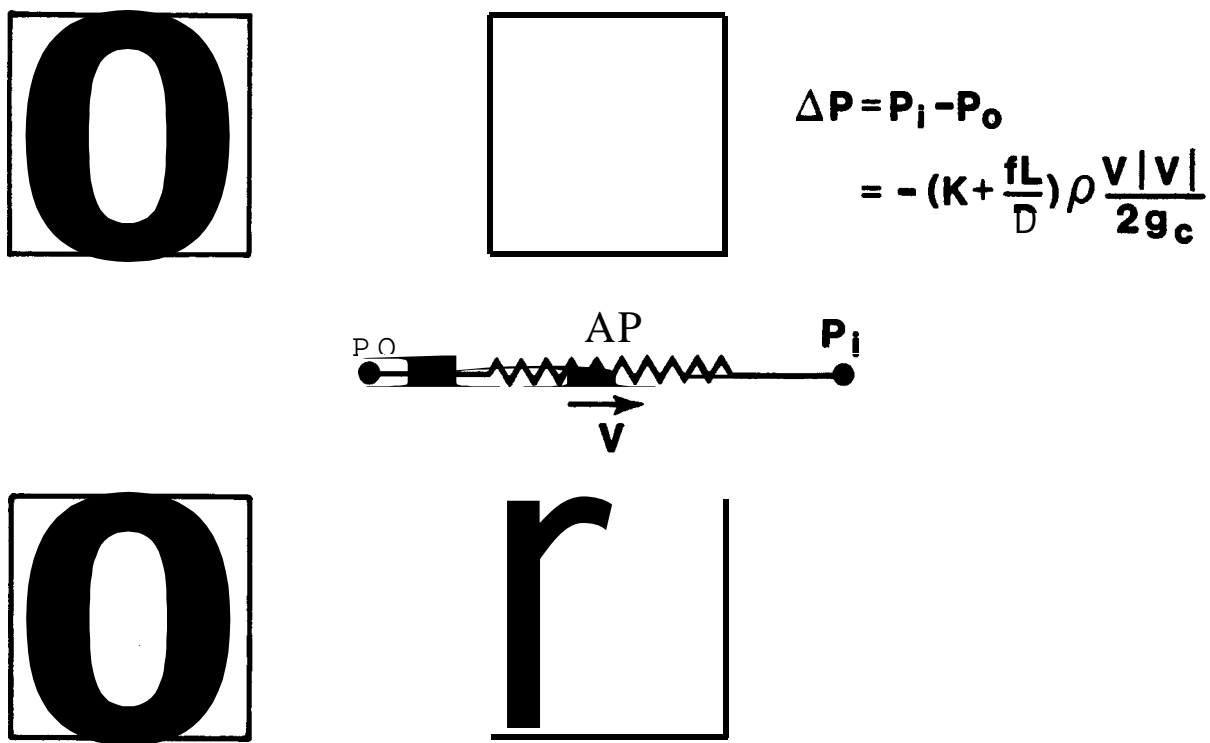


Figure 8b. Conservation of momentum.

greater detail below and in Appendices A and B. The calculated pressure differences are only due to flow between nodes since a common elevation is used for the momentum equation. Total pressure differences must include the static pressure due to elevation differences.

Assuming a constant fluid density for the oil, and substituting the momentum equation into the continuity equation, the combined **continuity-momentum** equation for each node can be written as

$$\frac{A_w}{a_w} P_w + \frac{A_e}{a_e} P_e + \frac{A_s}{a_s} P_s + \frac{A_n}{a_n} P_n - \left[ \frac{A_w}{a_w} + \frac{A_e}{a_e} + \frac{A_s}{a_s} + \frac{A_n}{a_n} \right] P_o = \Gamma^* \quad (4)$$

where

$$a_i = (K_{i-o} + f \frac{L}{D}) \frac{\rho |v_i|}{2 g_c} \quad (5)$$

and

$$\Gamma^* = \Gamma / \rho. \quad (6)$$

In the above equation, the pressures are the unknowns to be determined. Once the pressures are known, the velocities and mass flow rates can be easily determined. The equation set is non-linear since the coefficients depend on the answers; in this case, the velocities. Therefore, iteration is necessary and the coefficients must be recalculated after each iteration.

The above equation can be written for each node in the mine resulting in an **(NxN)** matrix for N nodes. In order to get a unique solution, the pressure at one node must be specified in the matrix since the momentum equation is in terms of pressure differences, not absolute pressures. For convenience, the pressure at the outlet node at the service shaft is the specified node. The other pressures are then the pressure relative to the

service shaft sump. Solution of the matrix is accomplished by a matrix solver. As a check on the results, after the mass flow rates between the nodes are determined, a check on the net mass flow is performed at each node in the system. The error in mass flow is 0.001% or less for all the nodes for the final solution.

In addition to the nonlinearity introduced into the equation set by the velocities, the friction factor and the K factors also have an effect. The friction factor is a function of the fluid velocities through the Reynolds number. The K factors are generally pressure loss factors for expansions or contractions, turns, and other mostly geometrical factors. In the present study, K factors from area changes (expansions and contractions), crosses, and elbows have been included. The K factors are slightly dependent on the results through changes in the calculated flow direction. The equations used for the friction factors and K factors are presented in Appendix A. The sensitivity of the results to the pressure loss coefficients is evaluated in Appendix B.

The velocities which are calculated by the above method are the average values. Typically, the velocity distribution has a large peak at the center of the duct, especially for laminar flow. However, such velocity distributions are derived for fully developed flow conditions. For a typical Reynolds number of 100, the velocity profile takes about 80 diameters to become fully established (White (1974)). The length of each corridor between intersections is about the same as the corridor equivalent diameter, so the flow will not be fully developed. Therefore, the velocity profile can be approximated as slug flow assuming that the corridor intersections result in a relatively uniform velocity profile.

### **III. Model Application**

The general model as given above can handle any number of nodes. However, in order to keep the analysis reasonable, the model was confined to the lower level. An evaluation of the flow through the upper level of the mine is presented in the results section. Due to the location of the fill holes and the service shaft in the southern portion of the mine, the entire east-west width was included in the model. The entire north-south length,

however, was not included. The model was expanded northward from the southern boundary until a negligible portion of the oil recirculated in the far north end. The final model included all the rows up through row R. Only about 1% of the recirculated oil goes north of rows O-P as will be evident from the results given in the next section. In addition, rows O and P were combined in the model.

Information on the dimensions (height, width, and length) of the various corridors is necessary for evaluation of the coefficients in the pressure matrix. The geometry of the mine is not precisely known since comprehensive documentation of the mine conversion activities was not performed. While the mine was surveyed by Rice before the mine conversion process as documented by Fenix and Sisson (1978a), the changes in the mine configuration due to backfilling, trenching, and many other mine conversion activities can only be estimated. Therefore, most of the parameters needed for this analysis can only be approximated.

The corridor dimensions have been estimated from the survey data of Rice (Fenix and Sisson (1978a)) along with data given in the mine volume report by Fenix and Sisson (1978b). The width of the corridors was determined by scaling the drawings of Rice (Fenix and Sisson (1978a)). The height of the corridors was determined from the mine volume report by Fenix and Sisson (1978b). For simplicity, the length of each corridor between intersections was assumed to be 100 feet in all cases. These numbers are approximate but are representative of the actual values. A number of changes were made to the mine due to mining after the survey date and in the mine conversion activity. Modifications include additional benching in the north area of the mine, additional drifts into the service shaft, the blasting of a number of salt bridges, and the addition of the fill holes. These changes were taken from various drawings which were shown earlier as Figures 3-6.

The oil is assumed to enter at the fill holes evenly divided between the east and west fill holes. Early calculations showed that a negligible amount of oil flowed between the two fill holes, so this connection was not included in later analyses. For analysis purposes, the fill hole drifts are connected directly to Rooms **15B** and 16B. The oil is assumed to exit at the service shaft at Room 3B. The details of the fill hole and service shaft rooms are not modelled; flow paths into and out of the rooms are

included, but any restrictions in the rooms themselves are not included in calculating the pressure differences and flow velocities. If the fill hole rates are unequal, the calculated mass flow rates and velocities in the area of the fill holes will change. However, the mass flow rates and velocities in the main area of the mine are insensitive to the exact split between the fill holes and will be primarily a function of the total mass flow rate.

For calculation of Reynolds numbers which are used in the friction factor evaluation as given in Appendix A, the density and viscosity of the oil is needed. For this study, the density and viscosity of the oil are 54.75 **lbm/ft<sup>3</sup>** and  $6.84 \times 10^{-3}$  **lbm/ft-sec**, respectively, based on data (BPS (1988)) and an assumed average oil temperature of 85°F.

#### IV. Results and Discussion

The design oil withdrawal rate is 593,000 BPD (PB-KBB (1982)). The velocity and mass flow rate results for the lower level of the mine are presented for oil recycle rates of 10% and 100% of the design withdrawal rate. These rates are chosen to bound the expected values and to indicate what, if any, flow pattern changes occur with different recycle rates.

Assuming that the fill holes are entirely full of oil (no underlying brine), the average velocity in the drifts entering Rooms 15B and **16B** is 0.016 **ft/sec** and 0.16 ft/sec for recycle rates of 59,300 and 593,000 BPD, respectively. The flow between the fill holes was found to be negligible in scoping studies, so this path was not included in the final model.

Figures 9-12 show the oil velocity and **mass** flow rate results for the main part of the mine for an oil recycle rate is equal to 10% **of** the design oil withdrawal rate, or 59,300 BPD. Two figures are needed for each variable since the magnitude of each parameter varies widely in the mine. Figure 9 shows the velocities in the lower level of the mine except around the service shaft (withdrawal location). Velocities around the service shaft are up to an order of magnitude higher than those in Figure 9 and are shown separately in Figure 10. The velocity in the fill hole drifts is **not** included in these figures. The length of the arrow indicates the magnitude of the velocity as scaled from the reference value. The velocities in the

main part of the mine are approximately 0.0001 **ft/sec** except around the service shaft where they reach about 0.0025 ft/sec in the drifts. Figures 11 and 12 show the mass flow rate distribution in the mine. The oil flow is mostly east to west and is contained below row H, which is the salt bridge row. The bridges which were blasted away at H6, **H16**, and H18 show a slightly higher velocity and mass flow rate than adjacent corridors.

Figures 13-16 show the same results as above for the oil recycle rate equal to the design oil withdrawal rate of 593,000 BPD. The results are similar to those shown in Figures 9-12 with the results being about a factor of 10 higher due to the higher recycle rate. The scale is also different by a factor of 10, so the same length arrow for a velocity or mass flow rate in both cases means that the results scale with the recycle rate. For the oil recycle rate of 593,000 BPD, the maximum velocities are about 0.001 **ft/sec** in the main part of the mine and up to 0.025 **ft/sec** around the service shaft. The flow pattern is only slightly different in the mine for this higher rate than for the lower rate.

For a recycle rate of 593,000 BPD, the velocities in the main part of the mine and in the area of the service shaft are low (**<0.025 ft/sec**) as discussed above. Therefore, brine movement in these areas during oil recycle exercises is considered to be unlikely. Brine movement in the fill holes due to an oil recycle exercise is the subject of a separate investigation and is not addressed in this report.

The pressure differences due to flow in the lower level are calculated to be very small. For an oil recycle rate of 593,000 BPD, the flow pressure difference between the main part of the lower level and the service shaft room is  $1.4 \times 10^{-6}$  psi, while the difference between the fill hole rooms and the service shaft room is about  $3.2 \times 10^{-5}$  psi. Static pressure differences of approximately 0.38 psi per foot of elevation difference are much greater than the flow pressure differences. These flow pressure differences are small due to very low oil velocities involved.

Based on these small pressure differences, the flow between the lower level and upper level through the nine drain holes and the upper level access drift is calculated to be less than 1% of the total flow rate as expected. Therefore, neglecting the upper level in calculation of the lower level pressures and velocities is acceptable.

→  
Velocity Scale = 0.0001 ft/sec

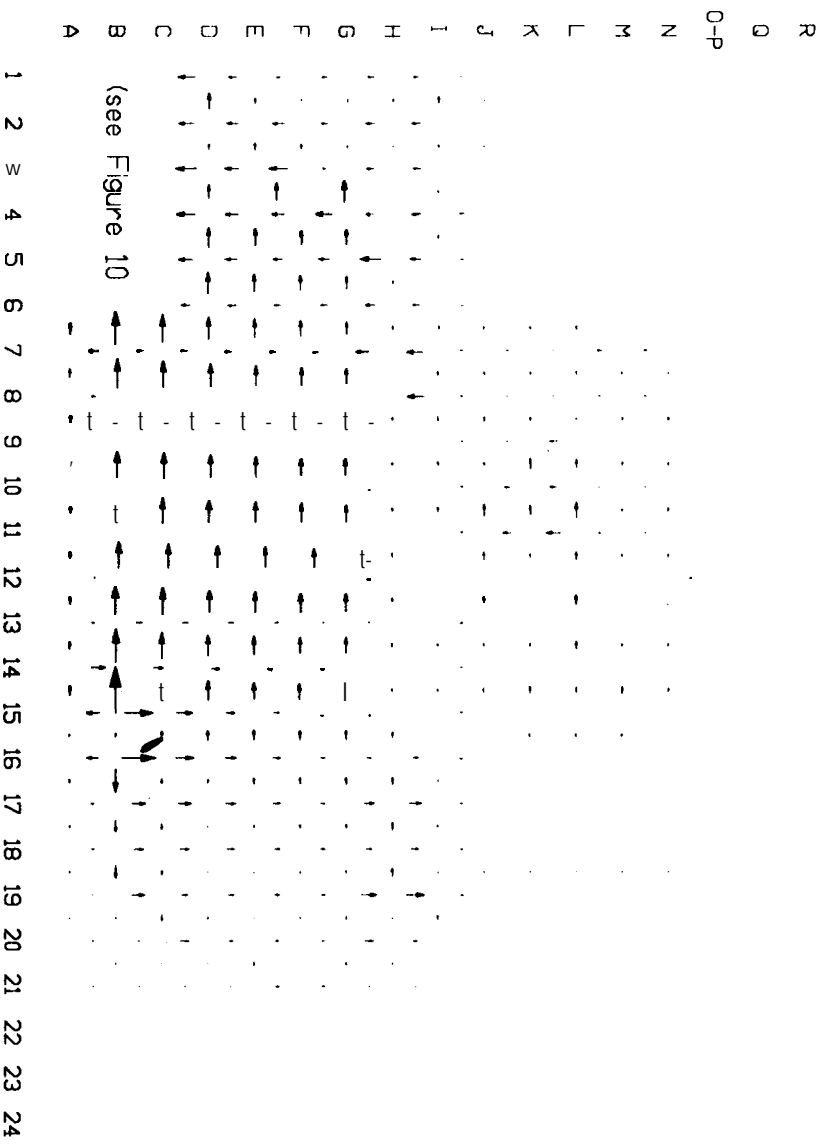


Figure 9. Lower level oil velocities.  
59,300 BPD.



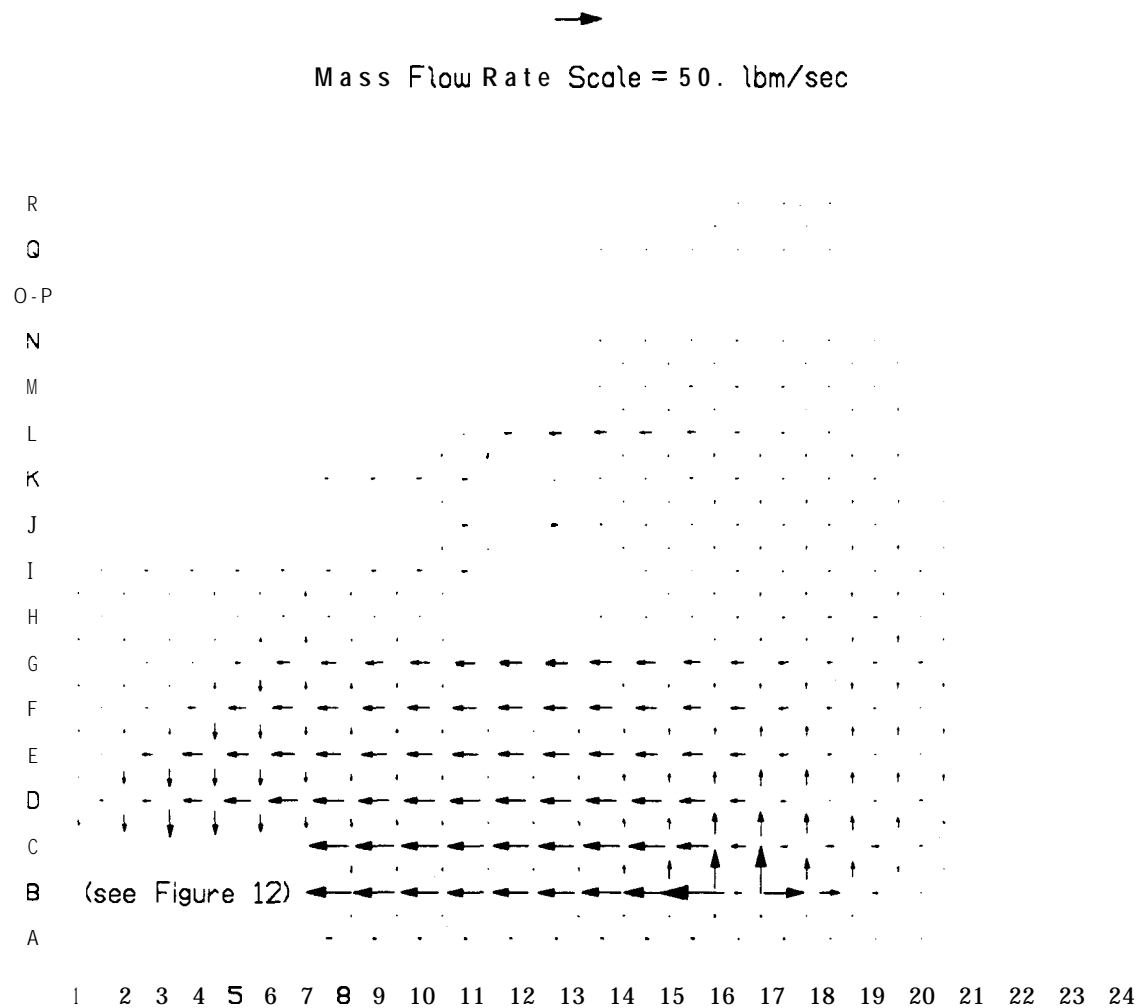


Figure 11. Lower level oil mass flow rates.  
59,300 BPD.

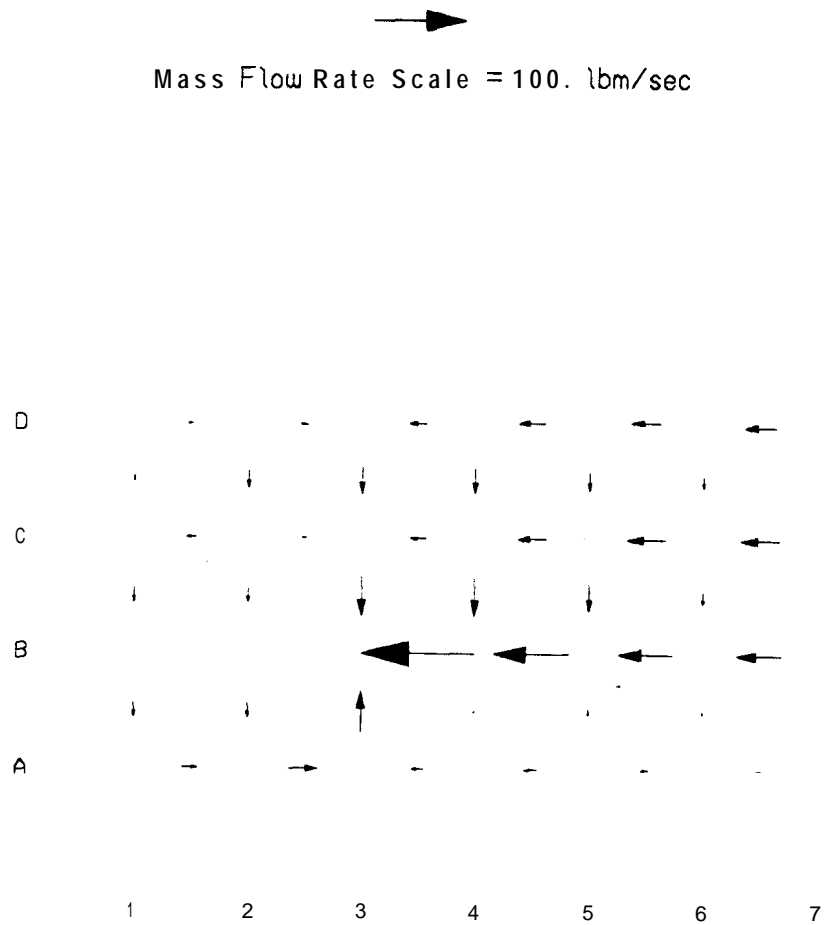


Figure 12. Service shaft area oil mass flow rates.  
59,300 BPD.

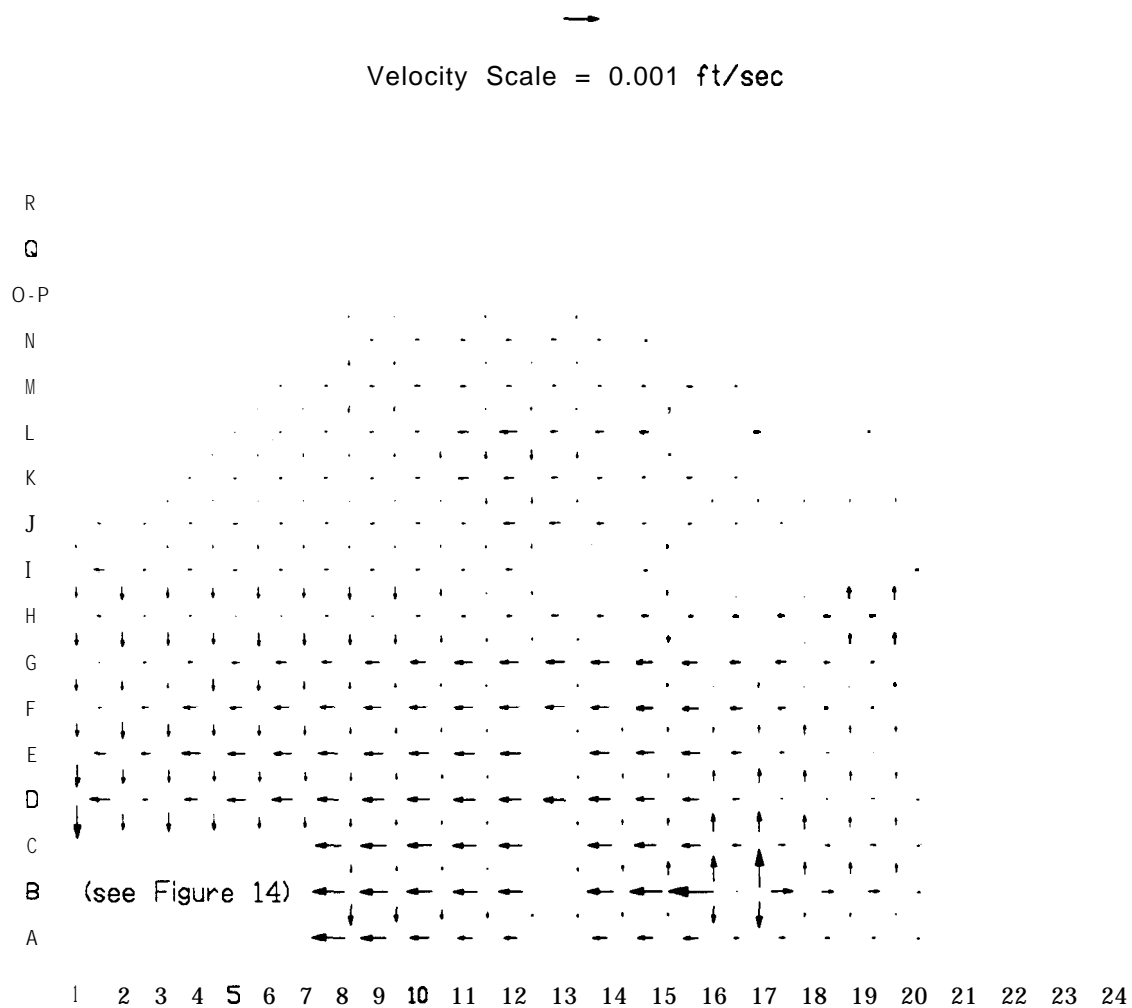


Figure 13. Lower level oil velocities.  
593,000 BPD.

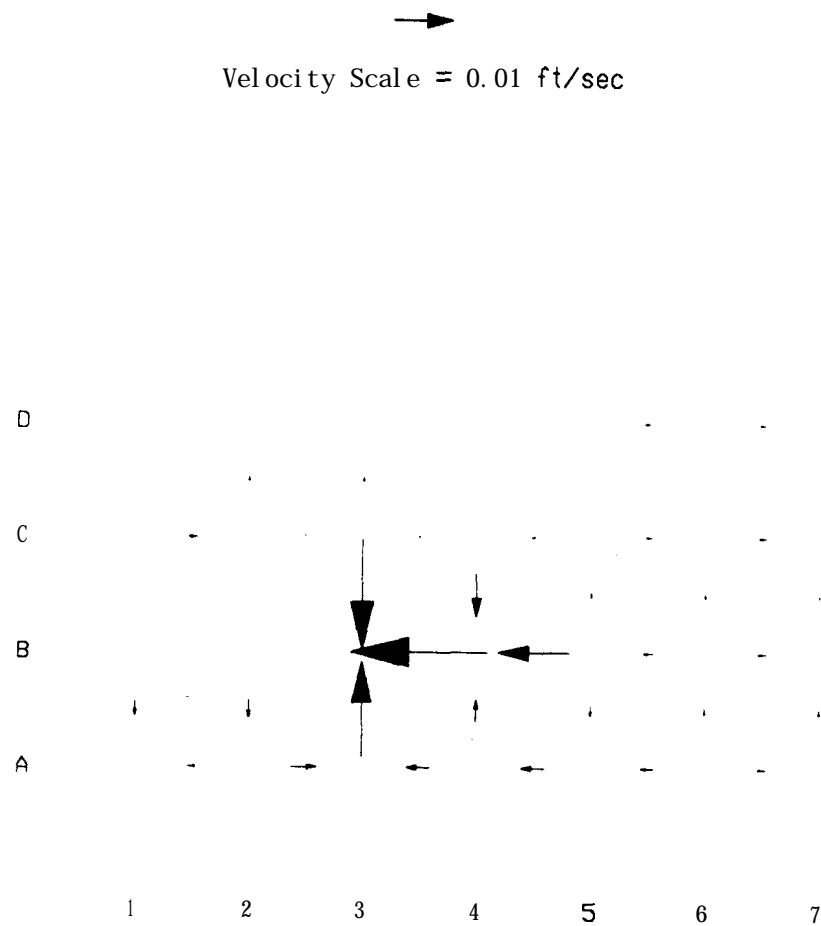


Figure 14. Service shaft area oil velocities.  
593,000 BPD.

→  
Mass Flow Rate Scale = 500. lbm/sec

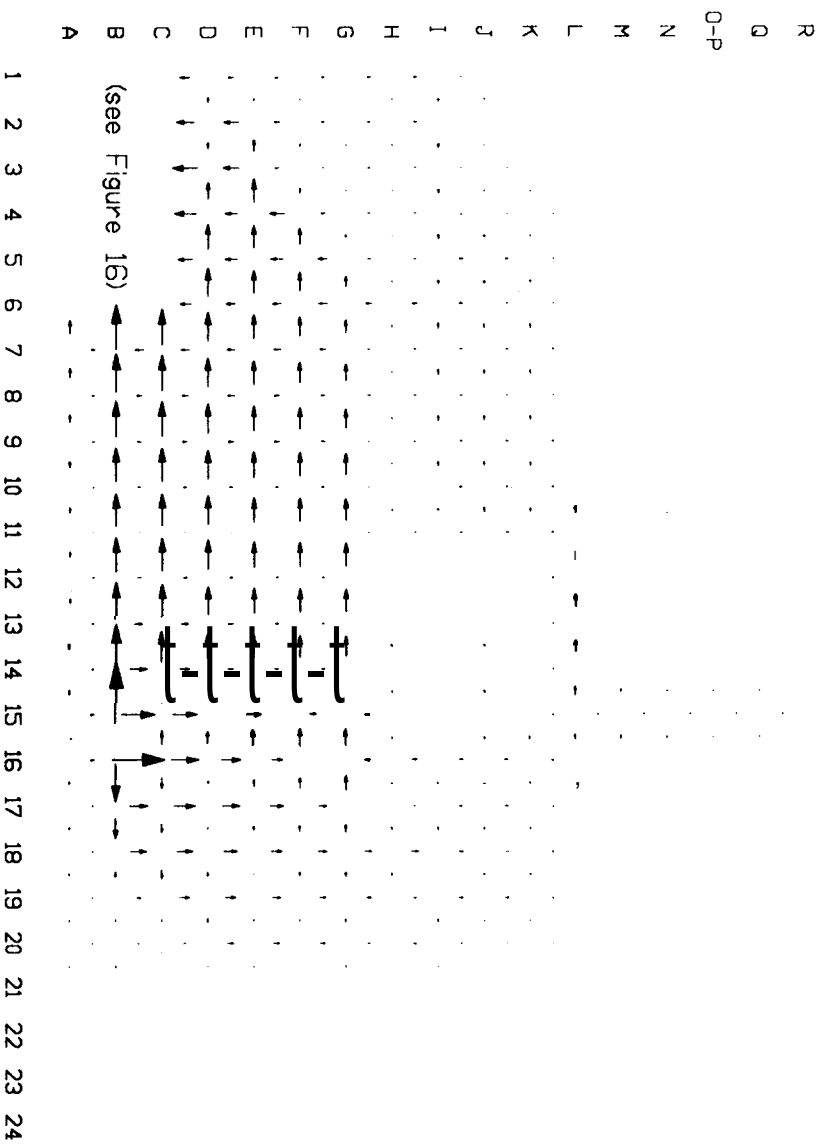


Figure 15 Lower level oil mass flow rates  
593,000 BPD.

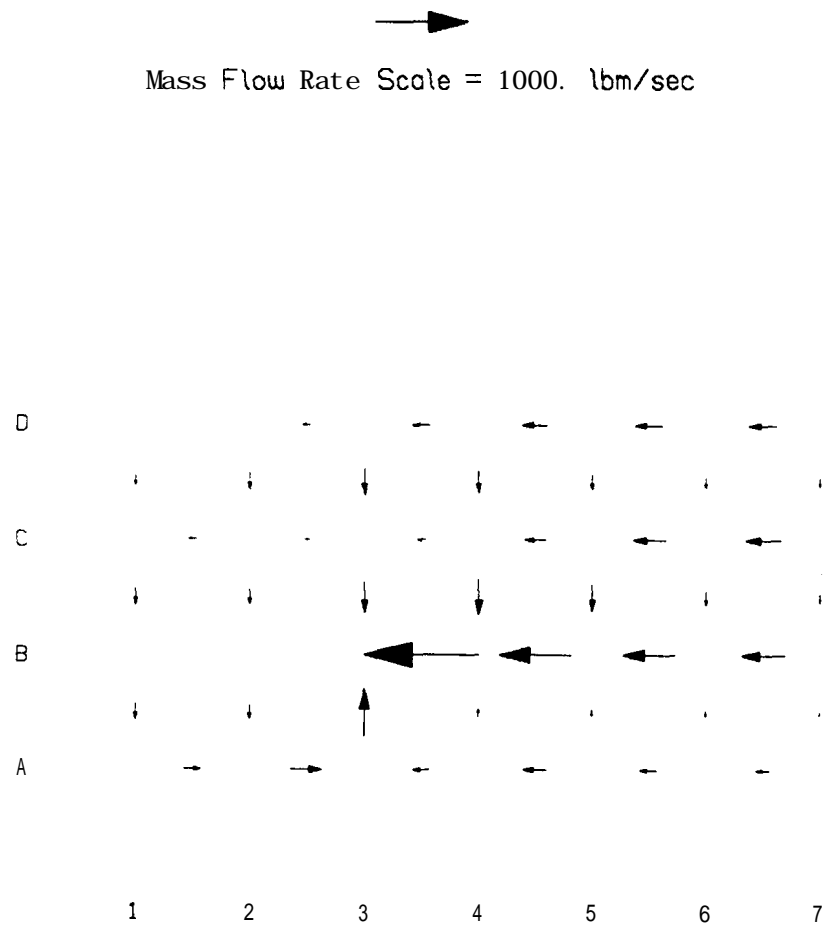


Figure 16. Service shaft area oil mass flow rates.  
593,000 BPD.

## V. Summary and Conclusions

Based on the oil recycle rate equal to the design oil withdrawal rate of 593,000 BPD, the oil velocities in the Weeks Island mine are very low. The velocities vary from 0.16 ft/sec in the fill hole drifts as they enter the mine, to approximately 0.001 ft/sec in the main part of the mine, and back up to 0.025 ft/sec around the service shaft. The oil flow in the lower level is mostly east to west below row H, which is the salt bridge row. Negligible flow through the upper level is calculated. The velocities vary approximately linearly with the oil recycle rate, and the flow pattern is essentially independent of the flow rate. Brine movement during oil recycle exercises is considered to be unlikely in the main area of the mine and around the service shaft due to the small velocities. Brine movement in the fill holes is being investigated separately.

The amount of oil involved in a recycle exercise is approximately one half the oil in the mine. Only the oil in the lower level south of rows O-P is significantly affected by recycle exercises. For oil that is involved, the minimum time for transport between the fill holes and the service shaft withdrawal location is about 23 days for a recycle rate of 593,000 BPD. This value is based on the distance of approximately 2000 feet between the fill holes and the service shaft and an oil velocity of 0.001 ft/sec. For lower recycle rates, the time will obviously be longer.

## VI. Nomenclature

$a$	coefficient
$A$	flow <b>area</b>
$D$	diameter
$f$	friction factor
$g_c$	gravitational constant
$K$	K factor (pressure loss factor)
$\dot{m}$	mass flow rate
$P$	pressure
$Re$	Reynolds number
$v$	local velocity
$V$	average velocity
$x,y$	coordinates

### Greek

$\epsilon$	surface roughness
$\rho$	density
$\mu$	viscosity
$\Gamma$	mass source rate
$\Gamma^*$	volumetric source rate

### Subscripts

<b>avg</b>	average value
<b>cont</b>	contraction
$e$	east
<b>exp</b>	expansion
$i$	node $i$
$n$	north
<b>o</b>	node $o$
$s$	south
$w$	west
$1$	<b>indice 1</b>
$2$	<b>indice 2</b>

## VII. References

Beasley, R. R., et al. (1985), Results of a Geotechnical Risk Assessment Study of the SPR Storage Facility at Weeks Island, Louisiana, SAND84 -2072, June 1985.

Boeing Petroleum Services (BPS), Inc. (1988), Quarterly Quality Program Status Report for the Quarter Ending September 30, 1988, US DOE SPR Report.

Crane Co. (1969), Flow of Fluids Through Valves, Fittings, and Pipe, Technical Paper No. 410, Crane Co., 1969.

Fenix and Sisson, Inc. (1978a), Drawings of Weeks Island Complex based on Rice Survey, 1-4-78 to 1-5-78.

Fenix and Sisson, Inc. (1978b), Calculation of the Storage Volume Available in the Weeks Island Mine, WI-22, March 1978.

Idel'chik, I. E. (1966), Handbook of Hydraulic Resistance - Coefficients of Local Resistance and Friction, AEC-tr-6630, NTIS, 1966.

PB-KBB (1982), Overview of Underground Construction Weeks Island Storage Site New Iberia, Louisiana, PB-KBB Inc., June 1982.

PB-KBB (1986), Weeks Island Risk Abatement Conceptual Plans, Draft Report, PB-KBB Inc., December 2, 1986.

Streeter, V. L. and E. B. Wylie (1975), Fluid Mechanics, Sixth Edition, McGraw-Hill Book Company, New York, 1975.

Webb, S. W. (1988), informal survey of the Markel Mine conducted on September 23, 1988.

White, F.M. (1974), Viscous Fluid Flow, McGraw-Hill Book Company, New York, 1974.

## Appendix A

### Friction Factor and K Factor Expressions

The pressure drop expression is

$$P_i - P_o = \left( K_{i-o} + f \frac{L}{D} \right) \frac{\rho V_i^2 I}{2 g_c} \quad (3)$$

Expressions for the friction factor,  $f$ , and the K factors are summarized below.

#### Friction Factor

The friction factor,  $f$ , is a function of the Reynolds number. For **laminar** and turbulent flow, the appropriate expressions are (Streeter and Wylie (1975)):

Laminar flow ( $Re < 2000$ )

$$f = 64 / Re \quad (A-1)$$

Turbulent Flow ( $Re > 2000$ )

$$\frac{1}{\sqrt{f}} = -0.86 \ln \left( \frac{\epsilon/D}{3.7} + \frac{2.51}{Re \sqrt{f}} \right) \quad (A-2)$$

and

$$Re = \frac{\rho V D}{\mu} \quad (A-3)$$

The term  $\epsilon/D$  is the relative roughness, or the dimension of the surface roughness,  $\epsilon$ , divided by the flow channel diameter. The roughness height of the mine surfaces is estimated to be about two **inches** based on an informal survey of the **Markel** Mine (Webb (1988)), the mine developed by Morton Salt after the DOE purchased the Weeks Island site (PB-KBB (1982)). For approximate corridor dimensions of 80-85 feet high and about 80 feet

wide, the value of  $\epsilon/D$  is approximately 0.002. From the Moody friction factor diagram in Streeter and Wylie (1975) and the friction factor expression given above, the approximate variation of the friction factor is

$$f = 64 / \text{Re} \quad \text{Re} \leq 2,000$$

$$f \sim 0.04 \quad \text{Re} = 4,000$$

$$f \sim 0.034 \quad \text{Re} = 10,000$$

Linear interpolation is used between the above values for Reynolds numbers greater than 2000.

### K Factors

In the present study, K factors from area changes (expansions and contractions), crosses, and elbows have been included. The following formulae have been used for expansions (Crane (1974)) and contractions:

$$K_{\text{exp}} = \left( 1 - \frac{A_1}{A_2} \right)^2 \quad (\text{A-4})$$

$$K_{\text{cont}} = 0.5 \left[ 1 - \left( \frac{A_1}{A_2} \right)^{0.75} \right] \quad (\text{A-5})$$

where  $A_1$  and  $A_2$  are the smaller and larger flow areas, respectively. The K factor is based on the flow area  $A_1$ .

K factors for the general situation of crosses for four intersecting flows have not been thoroughly studied. Some limited results have been presented by **Idel'chik** (1966) for crosses for converging (three flows in, one flow out) and diverging (one flow in, three flows out) situations, but the general case of two flows in and out has not been addressed.

The situation in crosses is similar to that in tees. If the flow is straight through a tee, the K factor is small. If the flow goes through

the branch, the K factor is significantly higher. The preliminary recommendation of Idel'chik (1966) is to use tee information for diverging crosses. From Crane (1974), the total K factor for flow through the run of a tee (straight through) is 0.2 while the K factor for flow through a branch is 0.6. Therefore, the split will be made as follows:

K = 0.1                      from tee entrance to intersection of the branch  
based on the tee entrance flow area

K = 0.1                      from intersection through the run  
based on the run flow area

K = 0.5                      from intersection to the branch  
based on the branch flow area

Determination of the run is made by determining the path with the greatest mass flow rate. Application to a couple of cases is shown in Figure A-1.

For elbows, the appropriate K factor is for sharp bends or miter bends. According to Crane (1974), the K factor for a miter bend is about 0.6 based on the elbow flow area, which is constant. Note that this value is the same as for flow in a tee that goes through the branch. Thus, the above logic for the tee results in the correct K factor for a miter bend.

#### Total Flow Path Resistance

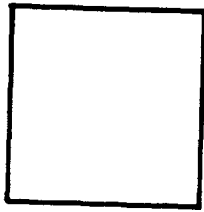
The flow path resistance is based on the summation of the friction factor and K factors based on the flow area used to calculate the velocity. To convert the friction factor or K factors from their individual flow areas to the velocity flow area, the values are multiplied by the ratio of flow area squared, or

$$K_{A_2} = K_{A_1} \left( \frac{A_2}{A_1} \right)^2 \quad (A-6)$$

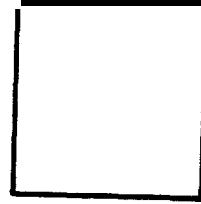
This equation changes the value of the K factor to give the correct pressure drop based on area  $A_2$  from that based on area  $A_1$ .

**cl**

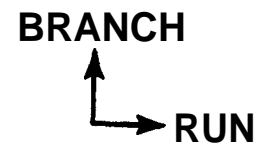
$$\frac{\dot{m}=100}{K=0.1}$$



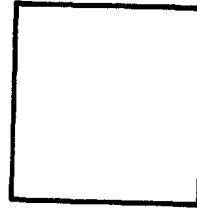
$$\begin{array}{c} \uparrow \\ \dot{m}=90 \\ K=0.5 \end{array}$$



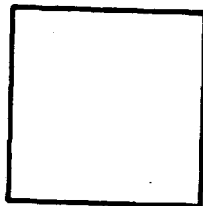
$$\frac{\dot{m}=20}{K=0.1}$$



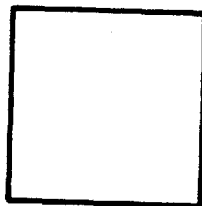
$$\begin{array}{c} \uparrow \\ \dot{m}=10 \\ K=0.5 \end{array}$$



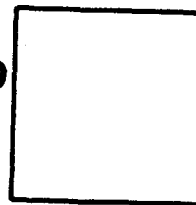
### CASE 1



$$\frac{\dot{m}=100}{K=0.5}$$



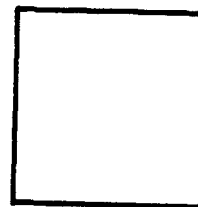
$$\begin{array}{c} \uparrow \\ \dot{m}=110 \\ K=0.1 \end{array}$$



$$\frac{\dot{m}=20}{K=0.5}$$



$$\begin{array}{c} \uparrow \\ \dot{m}=30 \\ K=0.1 \end{array}$$



### CASE 2

Figure A-1. K factors for crosses.

## **Appendix B**

### **Sensitivity of Results to Pressure Loss Terms**

The pressure loss terms in the present model are uncertain. The relative roughness used in the friction factor can only be estimated and the true value is unknown. The pressure loss factors for crosses are approximate since data are not generally available for this configuration. Since these factors are uncertain, the sensitivity of the results to these values has been assessed in this appendix.

The velocities and mass flow rates have been recalculated for the design recycle rate of 593,000 BPD with zero friction factors and all tee K factors (run and branch values) equal to 0.5. The area K factors given in Appendix A are still employed as is the procedure to calculate the total flow path resistance from the individual factors.

The results of this calculation are shown in Figures B-1 to B-4. The general flow pattern is similar to Figures 13-16 presented in the main report. Slightly larger velocities and flow rates through the northern part of the mine can be noted, but the overall effect is small. Therefore, the results given in this report are not sensitive to the friction factor or tee pressure loss procedure employed.

→  
Velocity Scale = 0.001 ft/sec

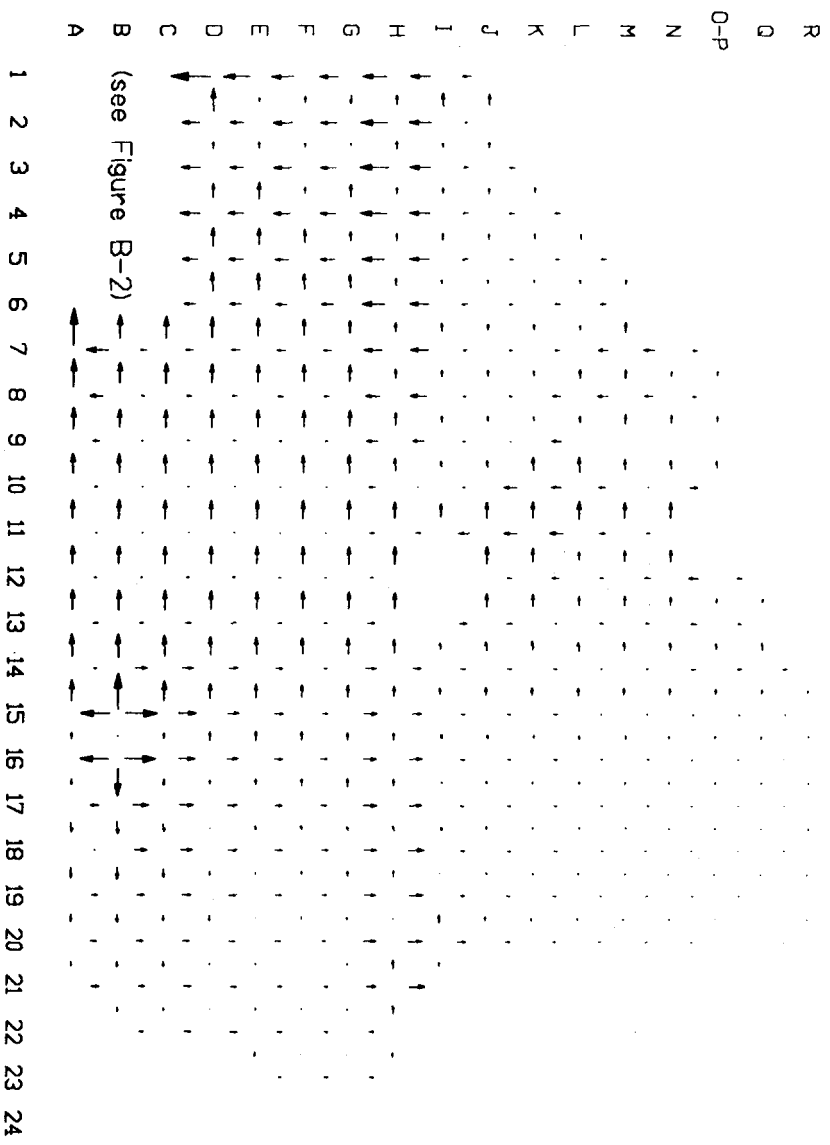


Figure B-1 Lower level oil velocities with revised pressure loss coefficients.



→  
Mass Flow Rate Scale = 500. lbm/sec

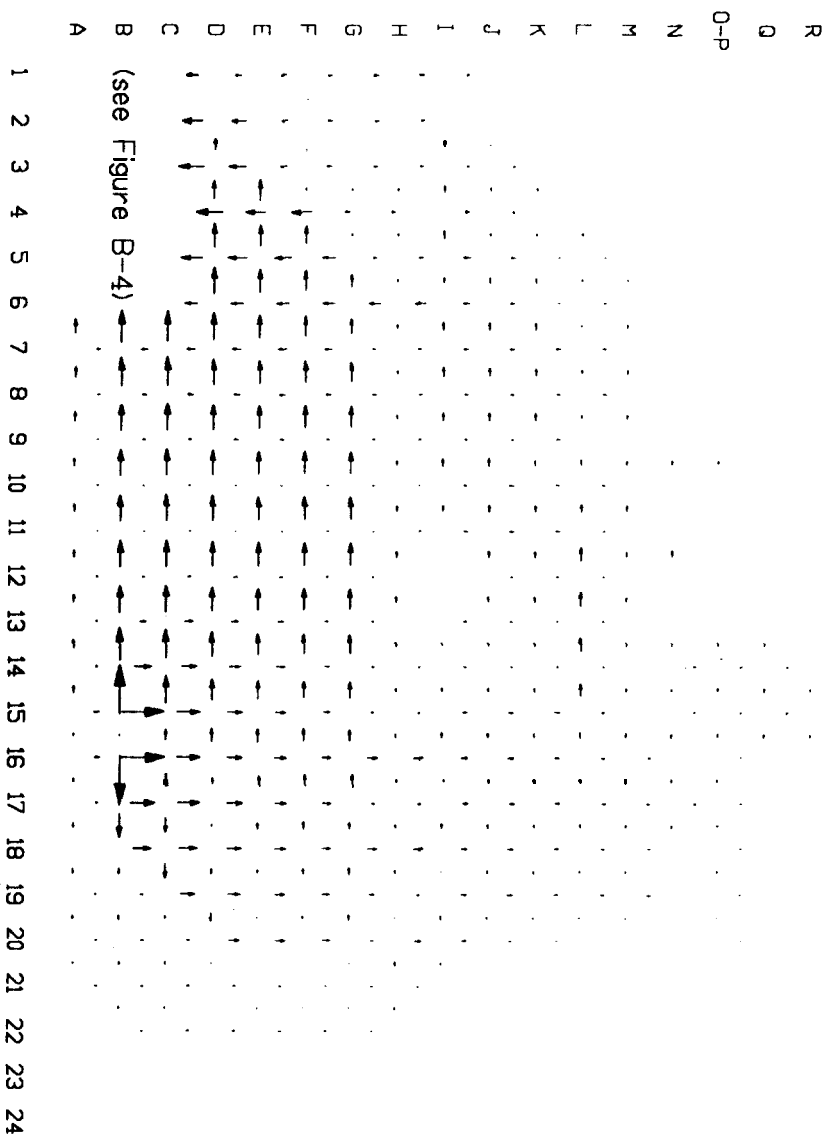


Figure B-3. Lower level oil mass flow rates with revised pressure loss coefficients.

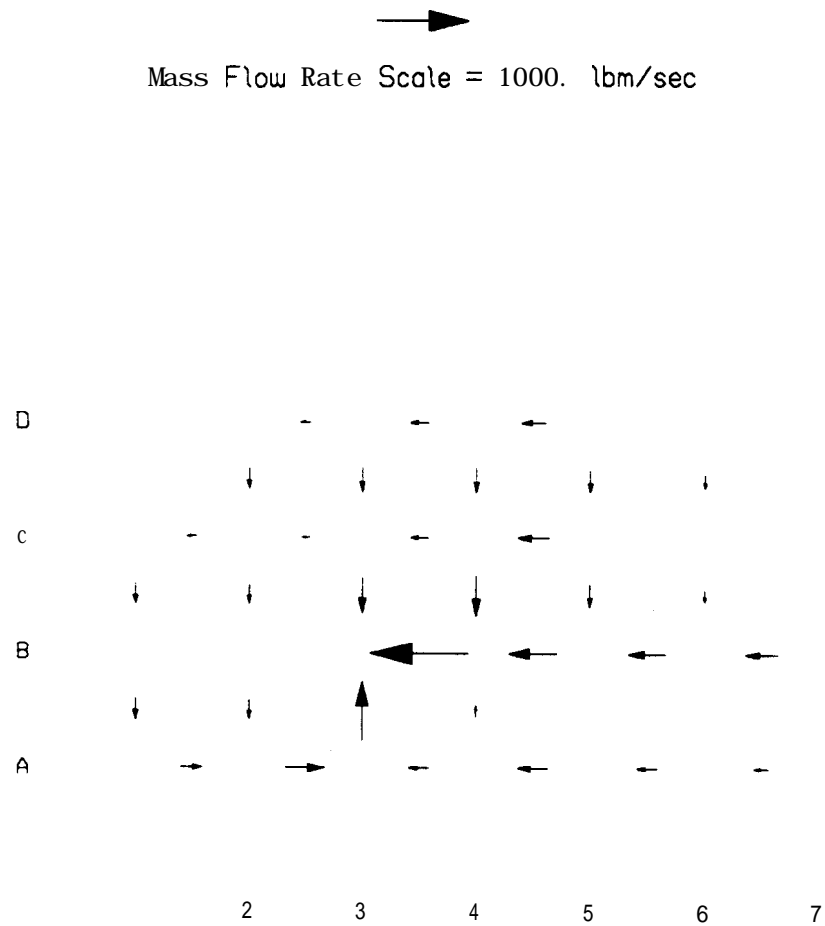


Figure B-4. Service shaft area oil mass flow rates with revised pressure loss coefficients.

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